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DEVELOPMENT OF A ROCKET-BORNE

INFRARED SPECTROMETER EMPLOYING

THE PRINCIPLES OF MOCK INTERFEROMETRY

by

Niels O. Young
Lawrence Mertz
John Armitage

Contract No. AF 19(604)-5738

Project No. 4904

Task No. 49045

Scientific Report No. 4

January 16, 1963

Prepared for

Geophysics Research Directorate
Air Force Cambridge Research Laboratory
Office of Aerospace Research
United States Air Force
Bedford, Massachusetts

Block Associates, Inc.
CAMBRIDGE 39, MASSACHUSETTS

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ABSTRACT

This report describes the development work undertaken by Block Associates, Inc., under Contract Number AF 19(604)-5738 to produce a rocket-borne infrared spectrometer employing the principles of "mock interferometry".

Development work centered around two main problems:

1. Design of a mechanical drive unit that would yield a "linear" reticle drive.

2. Design of an optical correction system to correct the field curvature produced by off-axis rays.

The first of these problems was eventually solved but no good solution to the second problem was discovered. The off-axis imaging problem can be ameliorated by using small entrance and exit apertures, but this limits throughput and resolution. The problem is not felt to be inherently insoluble and further work to devise an optical correction system is recommended.

Two technical papers pertinent to this contract are included as appendices.

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List of Illustrations

1.0 Background

The Mock Spectrometer is a new concept of spectrometer design. In theory, it will provide an instrument with the vibration resistance of a grating spectrometer and the high signal-to-noise ratio of an interferometer. Working models of an ultraviolet Mock Spectrometer had been constructed and had worked successfully. The work contracted for was to adapt this new concept to a rocket-borne spectrometer operating in the near infrared spectral region.

2.0 Theory of Operation

2.1 The Mock Interferometer is an instrument which simulates the performance of an interferometer. The justification for this simulation is that it yields the signal-to-noise advantages of inter- ference spectrometry, while preserving the more rugged mechanical struc- ture of a conventional Littrow spectrometer. The general physical arrangement is illustrated in Fig. 1. A Ronchi grating replaces the customary entrance and exit slits in the focal plane of a conventional Littrow spectrometer.

One interpretation of the operation of the instrument as a spectrometer is as follows. Imagine the spectrum produced by a con- ventional spectroscope. If all the light in the spectrum is added up or collected, we have a simple photometric measure of the source intensity. It is also possible to select sections of the spectrum by masking off the unwanted sections. The masks perform the same function as filters and give spectral information comparable to filter photometry. Each mask, or filter, allows us to measure one component of the spectrum. If the mask is in the form of a slit, such as the exit slit of a spectrometer, this corresponds to a narrow band filter. Different slit positions act as different filters and allow us to measure the intensity of different wavelength components of the spectrum.

Suppose now we mask the spectrum with a Ronchi grating. Such a mask produces a channel spectrum, and acts as a channel filter. The total transmitted power is proportional to the intensity of that spec- tral harmonic with which it is in register. The use of a set of Ronchi grating masks of different spacings would allow us to measure the intensity of as many harmonic components of the spectrum as there are masks. From such a set of components one can reconstruct the spectrum.

Clearly, we can displace the Ronchi grating by one line spac- ing without altering the masking properties. Alternatively we may shift the spectrum by one line spacing. Thus, many positions of the entrance slit will give the same transmission (neglecting vignetting).

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Clearly, we can displace the Ronchi grating by one line spac-ing without altering the masking properties. Alternatively we may shift the spectrum by one line spacing. Thus, many positions of the entrance slit will give the same transmission (neglecting vignetting).

The entrance slit can consequently be replaced by a Ronchi grating conjugate and corresponding to the one at the exit slit. The sole purpose of the entrance Ronchi grating instead of a single slit is to increase the light transmission of the instrument.

If, instead of employing a selection of differently spaced gratings, we rotate the exit Ronchi grating, then different components of the spacing of the Ronchi grating appear along the dispersion of the spectrum. It is necessary to skew the spectrum by rotating the entrance slits (Ronchi grating) as well, so that no individual wavelength of the spectrum crosses the Ronchi grating lines.

By simultaneous rotation of entrance and exit Ronchi gratings a continuous selection of harmonic components of the spectrum are available. The selection is only complete up to a maximum frequency harmonic component represented by the actual spacing of the Ronchi grating. Any orientation of the grating gives either that effective spacing or coarser, but never finer.

2.2 We will now calculate the spectral transmission of the device as a function of orientation of the Ronchi grating. Let us first imagine the operation with a non-dispersing Littrow system. Such a system will image the Ronchi grating back on to itself. Each Ronchi grating has an equi-spaced square wave whose transmission is either zero or unity. We can immediately state that the lines of that image will be parallel to the lines of the object Ronchi grating. If the bright lines of the image coincide with the transparent lines of the Ronchi grating, then the instrument will have a transmission of one half. On the other hand, if the bright lines of the image should coincide with the opaque lines of the Ronchi grating the system would not transmit at all. This leads to simplification in that we need only concern ourselves with the relative translation of object and image Ronchi grating.

During rotation of the object Ronchi grating there is one stationary point; namely the center of rotation. We will concern ourselves with the line of the Ronchi grating which goes through

that point. These are illustrated in Fig. 2 by the line through the point P. The stationary point P will be imaged into a stationary point P' and the line will be imaged into a parallel line through P'. Before continuing it should be made clear that the points P and P' need not be in the field of view.

Now if the separation of PP' is denoted by x, the relative translation of the object and image Ronchi grating is given by x sine θ, where θ is the orientation of the Ronchi grating. This leads to a transmission of

$$T = 1/2 \cos^2 (2\pi \frac{x \sin \theta}{s} + \varphi)$$

where s is the Ronchi grating spacing and φ is a constant which will now be established.

In Figure 3, we see close ups of object and image gratings for $\theta = 0$. In Figure 3, the center of rotation lies on the edge of one of the Ronchi grating lines. Bright lines of the image then coincide with opaque lines of the object Ronchi grating, yielding zero transmission, or $\varphi = \pi/2$. In Figure 4, the center of rotation lies on the center of one of the Ronchi grating lines. Bright image lines coincide with transparent object lines, T = 1/2 and $\varphi = 0$. In this manner, φ is established directly as a constant from the position of P on the object Ronchi grating.

Returning to Figure 2, we may now consider a dispersive Littrow image. In this case, P' will not be a unique point but will depend on the color of the light. In particular, we will disperse P' along the line PP', so that x will be a function of color. A linear approximation to this function can be made by

$$x = b (\nu - \nu_o)$$

where b expresses the dispersion in wave numbers per cm, and ν is the frequency of the light. ν_o is the color for which A would be imaged back on itself. The color ν_o is at our disposal and may be chosen within the observed spectrum or outside the spectrum, beyond either the red or blue end. The mechanism of the choice is in the positioning of the Ronchi grating drive axle with respect to the Littrow system.

Including the dispersion in our transmission formula yields

$$T = 1/2 \cos^2 \left(2\pi \frac{b(\nu - \nu_o)\sin \theta}{s} = \varphi\right)$$

Finally, we impose a non-linear scale on the orientation such that $t = \sin \theta$. If t is interpreted as a scanning parameter (time), then this non-linear scale change is facilitated by non-uniform rotation of the Ronchi grating. We now have the transmission

$$T = 1/2 \cos^2 \left(2\pi \frac{b(\nu - \nu_o) t}{s} = \varphi\right)$$

and this equation resembles the transmission of a Michelson interferometer at a retardation bt/s. The only difference, and it is an important difference, is that for a Michelson ν_o is necessarily zero, whereas with our "Mock Interferometer" can be freely chosen. In practice, in order to choose ν_o near to or in the spectral region being measured, the Ronchi grating is supported at its periphery with a hollow bearing. This permits the center of rotation P to be in or near the field of view.

2.3 The resemblance to interferometric transmission is more than superficial and the instrument lends itself extraordinarily well to spectroscopic applications. Unlike traditional interferometers, the instrument is not susceptible to slight misadjustments. The first prototype instrument was built and adjusted for large white light fringes within ten minutes after its original conception.

Doubts may arise concerning the linear approximation used for the dispersion of the instrument. Non-linearities in this dispersion do not in fact impair the functioning of the instrument. In the

process of Fourier transformation which is required for all two-beam interference spectroscopy, uniformly spaced samples in the dispersion become reconstructed as independent output points. If the dispersion is non-linear, a non-linear wave number scale appears at the output. While such a non-linear scale may be inconvenient, it is certainly as easy to calibrate as other spectrometers. The calibration may also be expected to remain just as stable, as it depends on the prism dispersion and position of A.

2.4 Further details of instrument operations are included in Appendix A.

3.0 Design History

3.1 Mechanical Problem

3.1.1 Crank and Slot Drives. The principal mechanical problem is the design of the grating drive. The Ronchi grating must be driven in a manner such that the sine of the driven angle is proportional to time. A crank and slot drive, with the shafts offset provides a first approximation to the desired motion. Design effort centered around building the necessary correction devices to make the drive produce output frequencies proportional to wavelength.

To correct the drive a variable crank length was used. The crank length was programmed by a cam and follower assembly. An initial version of this configuration was designed and built. A number of experiments were then conducted to determine its characteristics. The major problem was caused by the variable torque requirements. Since the needed motor torque varied with cam position, the speed of the synchronous motor varied. To deal with this problem a new drive unit was constructed. A flywheel was added to the motor and a spring was used to smooth the torque requirements over the cam cycle. During the flat portion of the cam cycle the motor acts to load the spring; during the steep portion of the cam cycle the spring unwinds to help the motor drive the cam.

This new configuration improved the operating characteristics of the motor drive. Further problems now appeared. Cam accuracy was not good enough and backlash in the gears became a problem.

A third drive arrangement was constructed using a more accurate cam and spring loaded gears. Experimentation was then done to find optimum cam follower spring tension. The resultant drive unit seemed satisfactory in most respects. The remaining problem was its short duty cycle. In spite of all the compensations and improvements that were added, the drive was still only linear during about one-quarter of its cycle. The remaining three-quarters had to be blanked out, with correspondingly short duty cycles. Duty cycles greater

than one-half will probably be exceedingly difficult to achieve due to the inertia of the drive components.

3.1.2 Non-linear Drives. There remains the possibility of ignoring the linear drive problem altogether and accepting a constant speed drive in which monochromatic fringe frequency is proportional to the sine of reticle position. With a corrected crank and slot drive each light frequency produces a unique audio frequency. Thus the total spectrum of incident radiation has a unique audio frequency spectrum which may be easily decoded by standard techniques of Fourier analysis. With a sinusoidal drive each light frequency has an associated audio spectrum rather than a unique single frequency. Since these spectra overlap almost completely, data reduction becomes quite difficult; standard wave analyzer techniques will no longer work. The interferogram must be digitized and analyzed by a computer. To do so accurately requires a very large number of samples per interferogram unless resolution is compromised.

3.2 Optical Problems

In the realm of optical problems, the major difficulty was the problem of off-axis imaging. If the instrument is to work properly the image of one Ronchi grating on the other must be in perfect alignment. That is to say, the imaged grating lines must be straight, parallel and in the same plane as the lines of the other Ronchi grating. If the entrance and exit apertures are kept small, this presents no problem. However, to obtain large throughput, large apertures are needed so that field curvature then becomes a problem. The incident off-axis rays are not properly aligned with the diffraction grating and so the image of the entrance Ronchi grating formed at the exit Ronchi grating is slightly curved. This field curvature prevents the instrument from working properly. The problem can be avoided by using small entrance and exit apertures, but this limits throughput and reduces the number of Ronchi grating lines used to produce the interferogram. Thus the number of resolution-elements in the field are reduced and resolution goes down accordingly.

An attempt was made to solve the problem by using a system involving separate entrance and exit Ronchi gratings. The exit Ronchi grating was to have curved slits so that it would be in alignment with the image of the entrance Ronchi grating. The necessary curvature was calculated and a trial instrument was built. This did not prove to be a feasible solution.

Another solution along similar lines was tried. The exit Ronchi grating was cut onto a spherical surface. After extensive experimentation, this design was also discarded as being unsuitable. The real problem with both types of correctors, the curved line Ronchi grating and the spherical Ronchi grating, is that they only correct image curvature without taking account of the geometry necessary for proper interferometer operation. Though they manage to align the image with the grating, they do so at the cost of causing variable spacing between the lines of the imaged grid and hence place the grating in register with a number of spectral harmonics at the same time.
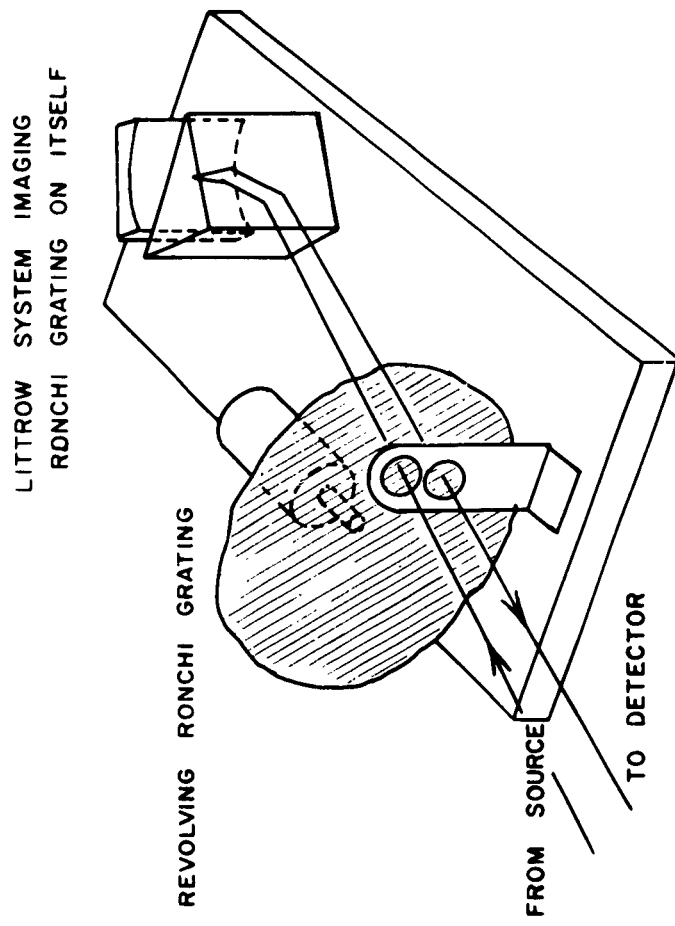
4.0 Summary and Recommendations

4.1 Summary. The project was concerned with adapting the principles of "mock interferometry" to a rocket-borne instrument operating in the near infrared spectral range. The major mechanical problem encountered was the construction of a drive unit that would rotate the Ronchi grating as a linear function of the sine of the driven angle. A crank and slot drive using a cam corrector was eventually developed to perform this task.

The major optical problem concerned correction of the field curvature resulting from off-axis rays. Extensive experimentation yielded no solution to this problem other than limiting the aperture size. Since such a solution also limits throughput and resolution it is not deemed to be very satisfactory. Figure 5 shows one of the experimental interferometers which was constructed.

4.2 Recommendation for Further Work. In spite of the problems mentioned above, we believe that "mock" interferometry is capable of providing a satisfactory rocket-borne spectrometer.

The crank and slot drive currently in use can probably be improved somewhat, but it is doubtful that a duty cycle greater than 50% will ever be obtained. If higher duty cycles than this are required, a constant angular-velocity drive appears to be the best method. Accordingly, further research to study the resultant data reduction problems is recommended. Digital techniques offer one very promising method.

We belive the off-axis imaging problem is more important than the drive problem since the potential gain in throughput is greater. However, further work on geometrical correction techniques seems undesirable. Optical correction techniques appear to offer the best approach to the problem. Accordingly, further research on prisms and corrector plates is recommended.

LITTROW SYSTEM IMAGING
RONCHI GRATING ON ITSELF

REVOLVING RONCHI GRATING

FROM SOURCE

TO DETECTOR

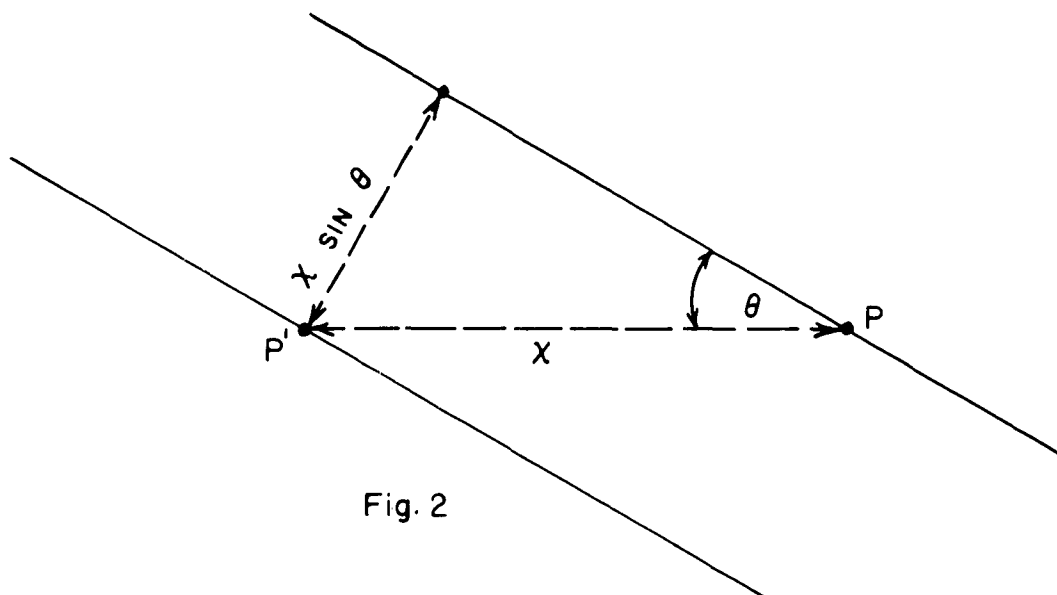MOCK INTERFEROMETER

FIGURE 1

Fig. 2

GRILL GEOMETRY
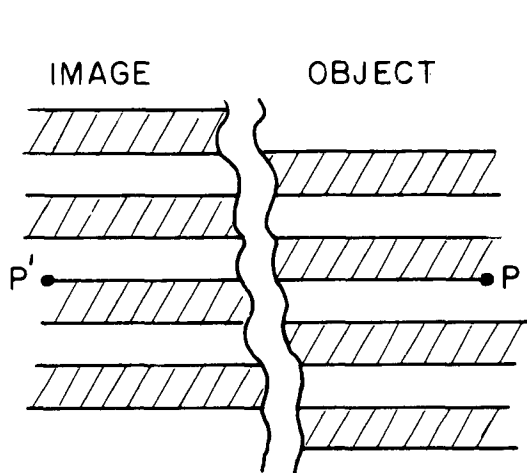
Fig. 3

OPTICAL IMAGING
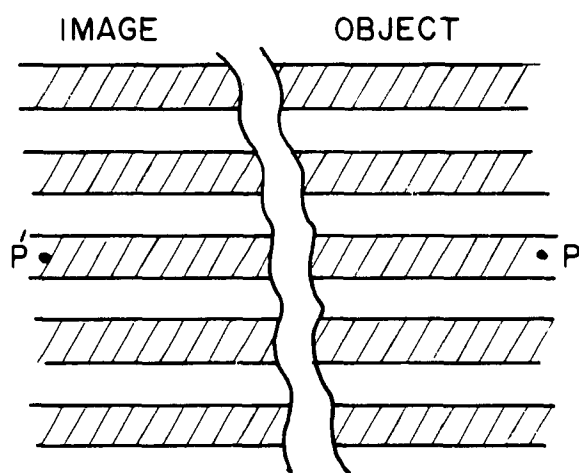
Fig. 4

OPTICAL IMAGING

Fig. 5   MOCK   INTERFEROMETER,
          EXPERIMENTAL   MODEL

MOCK   INTERFEROMETER
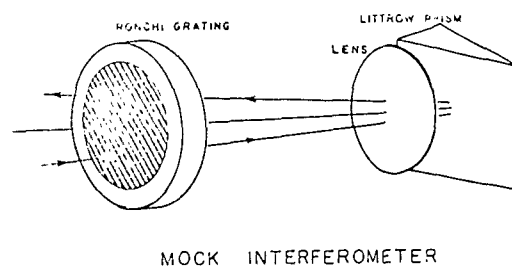
Fig. 6   LITTROW   OPTICAL   ARRANGEMENT
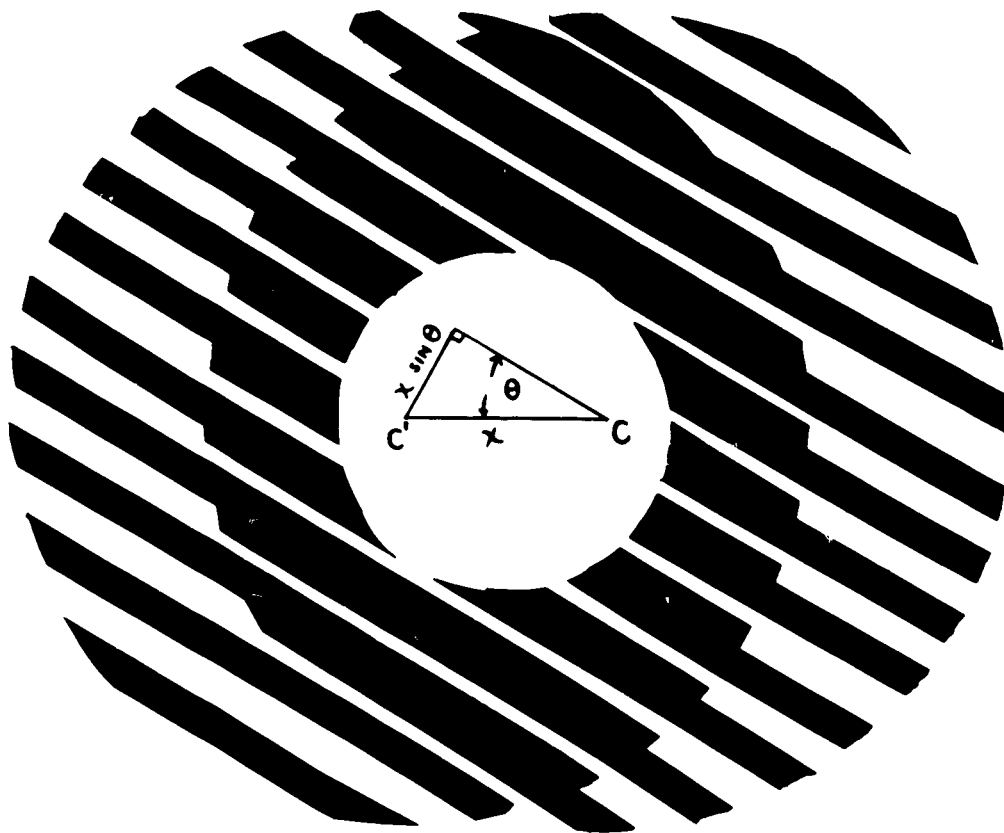
Fig. 7A   GRILL   GEOMETRY

Fig. 7B   GRILL   GEOMETRY

NEON SOURCE
PbS DETECTOR

Fig. 8   SAMPLE   INTERFEROMETER   SPECTRUM
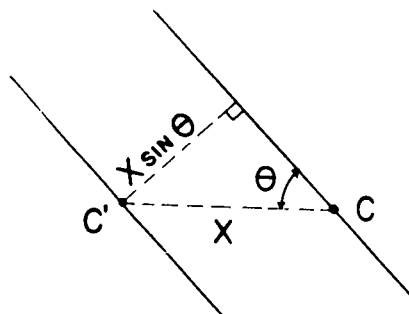
Appendix A: Mock Interferometry

A paper presented at the London Conference in July 1961, by L. Mertz
N. O. Young, and J. Armitage.

Mock Interferometry*

Summary -- A simulated interferometer for Fourier transform spectrometry is described with applications to diverse spectral regions (including ultra-violet) and to emission or absorption line profile studies. In addition to the usual advantages of interference spectrometry, i.e., Fellgett's multiplex advantage[1] of measuring all the colors simultaneously (applicable only in the infrared) and large acceptance angle at large aperture, i.e., large throughput, the "mock interferometer" has the following three advantages:

   1. The dimensional tolerances required are low, making it applicable to the ultraviolet as well as making it extremely durable under adverse operating conditions.

   2. It has no beam splitter problem and is applicable to any spectral region for which dispersers are available.

   3. The fringe frequency is not necessarily proportional to the radiation frequency. Therefore, by shifting the zero fringe frequency to the neighborhood of a small spectral region, only a low order (few harmonics) Fourier transformation need be used.

   Use of the "mock" interferometer does not, of course, eliminate the need for a Fourier transform computation to obtain the spectrum. This Fourier transformation may be performed with either digital or analogue techniques.

We call Mock Interferometry the simulation of the channel spectrum transmission, or Edser-Butler bands, of an interferometer. The idea is that if we reproduce such a transmission, regardless of how, we shall indeed have an instrument performing like an interferometer.

This transmission is achieved by the straightforward approach of placing a mask over the spectrum formed by a conventional spectroscope. The appropriate mask is clearly a uniformly spaced grill; a Ronchi grating. Now inasmuch as we are taking the overall light transmission through the grill and inasmuch as the grill has uniform spacing, it becomes possible to replace the entrance slit of the spectroscope with a conjugate grill. In this manner, we can let a lot more light through while retaining the spectral transmission characteristics.

For example, folding the system we find the Littrow arrangement illustrated in Figure 6. The entrance and exit grill are combined. One simply uses different regions of this grill for the entrance and exit bundles.

So far, only a single channel spacing has been mentioned. Complete simulation of an interferometer with variable path difference requires variable spacing. Otherwise we would be unable to scan fringes. This is the purpose of the rotating mount in the figure. When the grill is oriented with its lines parallel to the dispersion then the transmission depends on whether the grill is exactly imaged back on itself or with a slight shear. The white or black suggests the zero order transmission of a Michelson interferometer.

This resemblance was experimentally confirmed within ten minutes after its conception. We found that the fringes produced were indistinguishable by eye from those of a Michelson interferometer, and that we could readily scan through white light fringes by rotating the grill. Those of you who have ever sought white light fringes with a Michelson interferometer will appreciate the effortless achievement of white light fringes with even a primitive "mock" interferometer.

In order to develop a quantitative knowledge of the trans-
mission, we first notice that the lines of the image of the grill
for any color are necessarily parallel to the lines of the grill
itself. In other words, we have one large Moire fringe. Only the
lateral position of the image with respect to the grill determines
the transmission or the phase of the Moire fringe.

In Figure 7, the pertinent features of the grill system are
illustrated. This is a view through the grill, looking down the
optic axis. C is the center of rotation of the grill and C' is a
monochromatic image of C. These points are stationary. There is a
line shown through C representing the line of the grill which inter-
sects C. There is a corresponding parallel image line between C'.
With x as the distance CC' and θ as the angle between CC' and the
grill line through C, we find the shear of the image with respect to
the grill to be x sine θ.

The overall Moire transmission determined by this shear may
be expressed

$$T = 1/2 \cos^2 (2\pi \frac{x \sin \theta}{s} + \rho)$$

where s is the grill spacing and ρ is a constant. ρ is determined
solely by the position of C on the entrance grill. If the center of
rotation, C, lies precisely on the center of a grill line, $\rho = 0$.
If C lies on the edge of a grill line, then $\rho = 1/2\pi$. It should
also be pointed out here that the points C and C' need not lie within
the field of view.

We now make x a function of color, as a result of the dis-
persion. In simplest linear form, $x = b (v-v_o)$, where b is constant
and v_o is the color for which C' lies on C. Next we choose a para-
meter $\tau = \sin \theta$, and the transmission becomes

$$T = 1/2 \cos^2 \left[2\pi \frac{b(v-v_o)\tau}{s} + \varphi \right]$$

When $\varphi = C_1$ and $v_o = 0$, this is the transmission of a Michelson interferometer at retardation $b\tau/s$.

Nothing serious happens with non-linear dispersion. The wavenumber need not actually represent radiation frequency, but a color scale linearized to the dispersion. Measurements in terms of this color scale may later be calibrated into terms of the original radiation frequency. The same type of wavelength calibration is required of all prism spectrometers.

If the dispersing element of the Littrow spectrometer is a diffraction grating, then we find that the fringe frequency v is linear with wavelength (for small dispersion angles) as will be illustrated shortly.

The operation of the instrument proceeds as with systems of Fourier transform spectrometry involving Michelson interferometers. These techniques have found increasing use ever since their advantages were first realized by Fellgett and most of the details were presented at the Paris conference on Interference Spectroscopy in 1957 and at the Teddington conference on Interferometry in 1959.

The resolving power using the "mock" interferometer clearly cannot exceed the resolving power of the component Littrow spectrometer. For maximum resolving power, the grill should be as fine as the spectrometer will resolve. If the grill were made finer than this, no fringes would occur since the original Ronchi grating is not resolved.

A preliminary spectrum obtained with our "mock" interferometer is shown in Figure 8. This shows a neon spectrum obtained from our interferogram with fringe frequencies up to two kilocycles. Notice that the wavelength scale is linear, that long wavelengths have high fringe frequencies, and that zero fringe frequency lies near 5000Å.

This latter ability to locate zero fringe frequency in the spectrum at will allows us to achieve higher resolution than the size of our Fourier computation would normally permit. We expect this ability to be one of the fundamental merits of "mock" interferometry.

The instrument with which the neon spectrum was obtained is illustrated in Figure 9. Six seconds were used for recording signal on magnetic tape, and the source was a small neon lamp of about 1/4 watt.

The principal engineering problem is the construction of the drive such that sin θ is linear with time. So far, we have managed two approaches to the problem. The first approach was a rapid repetitive scan (2 1/2 scans per second) in order to make the output compatible with magnetic tape recording and audio frequency wave analysis[2]. This involves extremely non-uniform rotation and the accelerations and backlash prevented operation of a cam corrected drive. Instead, an approximate drive was made by using a crank and slot connection between offset shafts. It turns out to be important that the slot drive the crank, rather than vice versa, in order to approximate the desired motion. With this system, we are able to use a duty cycle of about 1/4, blanking the amplifier during the remaining 3/4 time, and we get about 1/2 the maximum resolution. By that, we mean we used the region $- 1/2 < \sin \theta < + 1/2$ for the measurement.

Another drive which we have recently constructed for the visible and ultraviolet, where we do not have low frequency detector noise and so can scan slowly, is an escapement with non-uniformly spaced teeth. The Fourier transformation in this case is readily adaptable to digital computation.

In conclusion, we would like to mention some of our desired applications of "mock" interferometry. Although Fellgett's multiplex gain is on the average balanced by the increased photon noise, the throughput gain is still available. With conventional spectrophotometers, it is impossible to decrease the slit width to gain resolution simply because the star image is too big.

We would also like to apply "mock" interferometry to the vacuum ultraviolet, not only for low resolution work but also for high resolution study of the Lyman α profile.

It has recently come to our attention that in 1959, Lohmann[3] mentioned the possibility of application of Moire fringes to spectral analysis. As has been seen, the "mock" interferometer also employs Moire fringe concepts although in a different way.

Finally, we would like to express our appreciation to the Geophysics Research Directorate for their support of this research.

REFERENCES

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2. Mertz, J.O.S.A., Advertisement, March (1960).
3. Lohmann, Optica Acta, 6, 37 (1959).

Appendix B: Heterodyne Interference Spectroscopy

A paper presented by L. Mertz at the ICO5 meeting in Stockholm,
August 1959. The Mock Interferometer is especially suited to
this application since its operation makes the use of a monoch-
romatic reference fringe unnecessary.

L. MERTZ, Block Associates, Inc., Cambridge,
Mass., U.S.A.

Heterodyne Interference Spectroscopy

The rapid response of modern photoelectric and thermal detectors
enlarges the realm for optical instrumentation. It is no longer neces-
sary to limit ourselves to instruments which were conceived with slow
visual or photographic detection in mind. In the past decade several
spectroscopic techniques have been developed to take advantage of rapid
detection. Examples are double-passing monochromators (Ref.1), multi-
slit spectrometry (Ref. 2), and SISAM (Ref. 3). Interferometric techni-
ques lend themselves admirably to such an approach, and enable one to
do away with slits. This ability to pass a large bundle of light is
particularly important (Ref. 4) for the energy limited detectors for
infrared spectral regions. The further advantage of simultaneous
measurement of all colors by using interferometric techniques has been
pointed out by Fellgett (Ref. 5). The object of this paper is to des-
cribe an interferometric method which should be suitable for the high
resolution measurement of absorption lines.

Let us now harken back to Michelson's technique (Ref. 6) of ob-
taining high spectral resolution by observing the visibility of inter-
ference fringes. I would like to briefly review his method, since it
forms a basis for the proposed techniques. Starting with an emission
spectrum line, one observes the visibility (or contrast) of the fringes
as a function of path difference with a Michelson interferometer. The
cosine Fourier transform of this visibility curve is the spectrum line
profile for symmetrical lines. For example, narrow lines have high
visibility fringes for large path differences, and double lines exhibit
beats in the visibility curve.

Even though his technique afforded the highest resolution in its
day, it had two fundamental drawbacks which prevented general acceptance.
One drawback was that the result is ambiguous in that the visibility of

the fringes discloses only the symmetrical part of the line profile. The second drawback was that it was only applicable to emission lines. Background light washes out the fringes so that absorption line spectrometry is impossible. The techniques of communication theory, coupled with rapid response detectors, should enable us to overcome both drawbacks.

The lacking unsymmetrical part of the line profile is related to the phase of the fringes. This corresponds to frequency modulation, just as the visibility curve corresponds to amplitude modulation of the fringes. Both modulations are amenable to the heterodyne techniques used in communication.

Suppose as we scan (see fig. 1) the Michelson interferometer fringes, we multiply them with other Michelson interferometer fringes from a known standard monochromatic source, and then only look at the lower resulting sideband in the vicinity of zero frequency. The appearance of the lower sideband depends on the phase of the monochromatic fringes. For this reason the two quadrature components are treated separately in figure 1. The unknown fringes are symmetrical and when multiplied by cosine monochromatic fringes yield a symmetrical result. This result is the cosine Fourier transform of the beat frequencies. Similarly, multiplication by sine monochromatic fringes yields the sine Fourier transform of the beat frequencies. Together these uniquely specify the unknown spectrum in the neighborhood of the known monochromatic reference line. In figure 1 the appropriate operations are shown in both the time space of the fringes and in the frequency space of the spectrum.

If we are to expect accurate results from this technique, we must be assured that the path difference for the reference monochromatic fringes precisely agrees with that for the unknown fringes. To achieve this accuracy I have built a variation of the Mach-Zehnder interferometer as shown in figure 2. The precision is built in, since it acts as two identical interferometers, each involving a different direction transmission over identical paths. All of the full mirrors are mounted on a single carriage, which slides in a direction normal to the plane of the beam splitter for scanning the fringes. The design of the instrument

allows for about $\pm$ 20 cm. path difference and has about 5 cm. aperture. Lead sulfide detectors are used for each channel although optional photoelectric detection is available for the reference channel.

A block diagram of the electronics is shown in figure 3. The multiplication is carried out with an ordinary phase sensitive demodulator, in which the reference fringes provide the signal that would otherwise come from a chopper. In our system a.c. is used but no chopper is necessary; scanning the fringes automatically provides a.c.

Provision is made for the electronic adjustment of the phase of the reference signal. Ideally the phase should be at 45° to the signal, since this gives equal in-phase and quadrature components. Another feature is that the reference fringe signal may undergo electronic frequency division. In this manner visible monochromatic sources may serve as reference for infrared regions. The only requirement is that a standard monochromatic line be available near some harmonic of the desired wavelength region.

The acceptance angle, i.e., the diameter of the central fringe, is that of a Michelson interferometer. At the large path differences required for high resolution, this angle may be undesirably small. It can be increased in the following way. Suppose that we have a Michelson interferometer and insert a plate of glass in one arm (Ref. 7). The plate of glass introduces an additional time delay in that arm. The arm would have to be shortened to obtain the zeroth order fringes. On the other hand, the arm actually appears shorter, just as a swimming pool appears shallower. If we extend the arm so that both arms appear to be equal length, then large diameter fringes occur. The acceptance angle has been increased and an even longer time delay occurs in the arm. Incidentally, it is the time delay which is essential to resolution.

In order to have maximum acceptance angle at all path differences, the glass thickness must be variable; so it would have to be constructed as a double-wedge compensator. One wedge would be driven across the other synchronously with the interferometer path difference.

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Such a fringe expander is similar to Connes (Ref. 8), and his could equally well be used. The acceptance angle with either is only limited by spherical aberration and is of the same order as that available with Connes spherical Fabry-Perot (Ref. 9). I might add that although I have verified the fringe expansion with a cube-corner Michelson interferometer, I do not expect to include the feature on the first model of the heterodyne interferometer.

In conclusion, I would like to summarize the vices and virtues of heterodyne interferometry.

The chief deficiency is that the measurements must be transformed to yield a spectrum. Straightforward, high-quality Fourier transformation can now be carried out on digital computers. However, in heterodyne work I anticipate that careful sorting and weighting of the sine and cosine parts will have to be done.

A second deficiency is that a monochromatic reference line must be available near some harmonic of the desired spectral band.

On the merit side, there are several advantages. The precision inherits directly from that of the monochromatic reference, without mechanical intermediate standards such as gratings, lead screws, or spacings. Relatively crude optics are permissible.

Secondly, the results are not entangled with overlapping orders so that absorption line spectrometry may be carried out with little or no prefiltering.

Thirdly, a large acceptance angle is available for limited brightness sources. Furthermore, a corrector may be included to further increase the acceptance angle for very high resolution.

Finally, the wavelengths of the unknown spectrum are measured simultaneously, thus yielding Fellgett's (Ref. 5) signal-to-noise improvement.

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